2

AEDC-TR-66-146

cy 1

AN EXPERIMENTAL INVESTIGATION OF MIXING HIGH TEMPERATURE AIR WITH AMBIENT BYPASS AIR BY UPSTREAM INJECTION

J. R. Henson, ARO, Inc.
and
C. E. Simmons, 1st Lt, USAF

November 1966

Distribution of this document is unlimited.

PROPULSION WIND TUNNEL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

AN EXPERIMENTAL INVESTIGATION OF MIXING HIGH TEMPERATURE AIR WITH AMBIENT BYPASS AIR BY UPSTREAM INJECTION

J. R. Henson, ARO, Inc.

and

C. E. Simmons, 1st Lt, USAF

Distribution of this document is unlimited.

FOREWORD

The information reported herein was compiled as a result of an experimental investigation sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC) under Program Element 62410034/7778, Task 777805.

The results of research presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, Arnold Air Force Station, Tennessee, under Contract AF 40(600)-1200. The research was conducted from November 1965 through January 1966 in the Propulsion Wind Tunnel Facility, under ARO Project No. PL3535. The manuscript was submitted for publication in July 13, 1966.

This technical report has been reviewed and is approved.

C. E. Simmons
1/Lt, USAF
Research Division
Directorate of Plans and Technology

Donald R. Eastman
Acting Director
Directorate of Plans and Technology

ABSTRACT

A mixing chamber employing upstream injection of the secondary airflow was designed and tested in conjunction with a Mach 4.0 nozzle. Mixing chamber configurations with total length to maximum diameter ratios of 1.7 and 2.3 were investigated. The mixer was designed for a secondary to primary mass flow ratio of 2.57 and a primary to stilling chamber pressure ratio of 4.78. A uniform temperature profile with not more than 5 percent variation at the exit of the Mach 4.0 nozzle was required. The mixing chamber was experimentally investigated at secondary to primary mass flow ratios of 0.86 to 2.70. The primary mass flow ranged from 0.99 to 1.5 lb/sec at temperatures from 1730 to 2240°R, depending upon the heater flow rate. The secondary flow temperature was approximately 470°R. Temperature and pressure profiles obtained in the mixing chamber and 0.5 in. downstream of the Mach 4.0 nozzle exit substantiated satisfactory mixer performance.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

A	Area
a	Sonic velocity
C_p	Specific heat
D	Maximum mixer diameter
d	Mixer diameter at secondary injection ports
d_i	Secondary injection port diameter
K	$g\sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$
L	Total mixer length (choked throat inlet to Mach 4.0 nozzle inlet)
M	Mach number
$\dot{m}$	Mass flow

p	Static pressure
p_o	Pitot pressure
R	Universal gas constant
T	Static temperature
T_o	Total temperature
V	Velocity
γ	Ratio of specific heats

SUBSCRIPTS

1	Secondary air manifold
2	Secondary air line upstream of venturi
3	Mach 4.0 nozzle exit
4	Test cell
5	Expansion section surface
6	Stilling chamber surface
c	Mixer stilling chamber
H	Heater exit
NE	0.5 in. downstream of Mach 4.0 nozzle exit
p	Primary airflow
s	Secondary airflow
x	Flow conditions at injection point in chamber
*	Sonic conditions in choked nozzle throat
**	Sonic conditions in Mach 4.0 nozzle throat

SECTION I
INTRODUCTION

The process of mixing two airflows, initially at different pressure and temperature levels, to produce a third specified pressure and temperature condition is important in a number of fluid dynamic applications. The normal method of combining gas streams to obtain one stream with reasonably uniform pressure and temperature profiles has been by co-axial mixing. However, co-axial mixing requires the physical mixer to be ten to twenty diameters in length. Certain applications exist where the process of combining two different energy level airflows must occur within a mixer length to diameter (L/D) ratio of 2 to 3.

In the present study, the feasibility of obtaining adequate mixing with a short mixer employing injection of the airflows at an obtuse angle relative to each other was experimentally investigated. The effects on mixing performance of variations of the high temperature (primary) airflow, cool (secondary) airflow, secondary flow injection angle and location, and mixer length were investigated in conjunction with a Mach 4 nozzle. Pressure and temperature distributions at the mixing chamber exit and at the exit of the Mach 4 nozzle were obtained.

SECTION II
APPARATUS

2.1 GENERAL DESCRIPTION

The mixing chamber was tested in conjunction with equipment developed for a previous investigation. The test equipment consisted of an air supply system, an air heater system, a mixing chamber, a Mach 4.0 nozzle, and a test cell with ducting to the Rocket Test Facility (RTF) exhauster system. The mixing chamber consisted of a choked nozzle, an expansion section which included the secondary injection system, and a constant diameter section which acted as a stilling chamber for the Mach 4.0 nozzle. The test equipment including the mixing chamber is shown in Figs. 1 and 2. The mixing chamber and Mach 4.0 nozzle dimensions are presented in Fig. 3.

2.2 AIR SUPPLY SYSTEM

Air for the test was piped from the 4,000-psia storage bottle at the von Kármán Gas Dynamics Facility (VKF) to the test area. The air was divided by a ducting arrangement to supply both the heater and the secondary injection system. Separate mass flow controls and pressure regulating valves were provided for the heater and secondary injection systems. Mass flow through the heater was monitored by measuring the stagnation pressure and temperature in the stilling chamber upstream of the choked nozzle. The mass flow rate through the bypass system was obtained by monitoring the pressure and temperature forward of a calibrated choked venturi.

2.3 AIR HEATER SYSTEM

The primary airflow was heated in an electrical resistance heater by flowing in direct contact with six elements, whose temperature could be maintained at a maximum operating temperature of 2460°R. This heater is capable of continuously delivering 5 lb/sec of air at a temperature of approximately 2000°R. Heater power was supplied by a regulated d-c power supply, and the required input power levels to the heater were determined by monitoring the element temperatures and output air total temperature.

2.4 MIXING CHAMBER

The mixing chamber, located between the air heater system and the Mach 4.0 expansion nozzle, consisted of a choked nozzle, an expansion section, and a constant diameter section. The total length of the mixing chamber was 23.02 in. An adapter downstream of the constant diameter section provided a transition between the chamber and the expansion nozzle inlet as shown in Fig. 3.

2.4.1 Choked Nozzle

The choked nozzle used for the present tests was the throat section of a Mach 7.0 nozzle. The mixing chamber analysis, outlined in the Appendix, used the throat area ratio 0.093, which is the area ratio of the choked nozzle throat to the Mach 4.0 expansion nozzle throat. At the assumed secondary to primary mass flow ratio of 2.57 to 1 a pressure ratio, p_{o_H}/p_{o_C}, of 4.78 to 1 was calculated for the primary flow.

The choked nozzle was an axisymmetric, contoured nozzle whose contour consisted of a circular arc to the throat and an assumed cubic area distribution from the throat to the exit. The throat diameter was 0.694 in., and the exit diameter of the throat section was 2.200 in. This section was water jacketed to provide backside cooling.

2.4.2 Expansion Section

Two 30-deg half-angle expansion sections were tested with upstream secondary port injection angles of 45 or 60 deg. The injection angles are measured from the mixing chamber centerline. Injection of the secondary air was accomplished in the divergent section through eight peripheral, 0.75-in.-diam ports located symmetrically around the chamber. The intersection of injection flow centerlines with the chamber centerline was 6.98 and 7.84 throat diameters downstream from the choked nozzle minimum for the 45- and 60-deg expansion sections, respectively. Figure 4 presents a photograph of one of the expansion sections showing the eight secondary air injection ports. The eight ports were connected to a common manifold and secondary air at a temperature of approximately 470°R was delivered to the mixer manifold at two points located 180 deg apart.

2.4.3 Stilling Chamber

A 5.92-in.-long, 10.02-in. constant diameter section was attached to the exit of the expansion section and served as the stilling chamber for the Mach 4.0 nozzle. Tests were conducted with and without the constant diameter section.

2.5 EXPANSION NOZZLE

The Mach 4.0 expansion nozzle was an axisymmetric contoured nozzle. The nozzle contour consisted of a circular arc to the throat, an assumed cubic area distribution from the throat to the inflection point, and a corrected potential flow characteristic solution from the inflection point to the exit. Calculation of the potential flow contours was carried out using the method of Cresci which is described in Ref. 1. Viscous flow corrections were made to the contours by the method of Sivells given in Ref. 2. The throat diameter of this nozzle was 2.277 in., and the exit diameter was 8.0 in.

The nozzle throat section was water jacketed to provide backside cooling, and the downstream expansion section was cooled with backside cooling coils, as shown in Fig. 3.

The nozzle flow exhausted into the test cell, which was maintained at a static pressure of approximately 0.5 psia by the Rocket Test Facility (RTF), AEDC, exhauster system.

2.6 INSTRUMENTATION

The instrumentation used in this investigation can be classed as component control instrumentation, supply air instrumentation, or test instrumentation. Component control instrumentation refers to instruments used to control or monitor the operation of the equipment. Supply air instrumentation was used to monitor the condition of the test air within the various components. Test instrumentation consisted of the stagnation pressure and temperature probes which traversed the Mach 4.0 expansion nozzle stilling chamber and exit plane. Figure 5 shows the locations of the instrumentation. All instrument outputs were observed on gages or recorded on millivolt recorders in the control room.

2.6.1 Component Control Instrumentation

The input power to the heater was determined by monitoring heater element temperatures and the output air temperature. Heater element temperatures were measured with platinum-rhodium thermocouples attached to the heater elements. The maximum allowable element temperature was 2460°R. To determine the amount of power that was being delivered to the heater, the d-c voltage and current were monitored at the output of the power supply. To insure that the heater shell did not exceed the design operating temperature, iron-constantan thermocouples placed at several locations on the heater surface and flange liner were monitored. Surface temperature measurements were also made on the mixing chamber wall.

Since the nozzles were water-cooled, instrumentation was supplied to observe the pressure, temperature, and flow rate of the cooling water in each nozzle. An interlock on this instrumentation was provided so that the failure of one system, such as the cooling water or power supply, automatically shut the entire test rig down. Exhauster pressure was obtained from a wall pressure measurement in the test cell.

2.6.2 Supply Air Instrumentation

The pitot pressure and total temperature of the primary airflow were measured with probes in the flow at the heater exit. The heater (or primary) mass flow was determined from these exit pressure and temperature measurements. The secondary mass flow was determined from the air temperature and pressure upstream of the choked venturi in the supply line.

Additional instrumentation was used to measure the static pressure in the stilling chamber, the pressure in the secondary injection manifold, and wall pressure and temperature at the exit of the Mach 4.0 nozzle.

2.6.3 Test Instrumentation

Profile measurements in the stilling chamber of the Mach 4.0 nozzle were made with either a pitot pressure or a total temperature probe. Simultaneous measurements were not taken since only a single probe mount was available. The stilling chamber probe was retracted to the wall when data were being recorded at the nozzle exit.

The nozzle exit pressure and temperature profiles were made from data obtained by a dual measuring probe located at a point 0.5 in. downstream of the nozzle exit. This probe was manually operated and simultaneously measured the pitot pressure and total temperature. The pressure and temperature measuring points were 1.0 in. apart.

2.6.4 Accuracy of Instrumentation

Pressures were measured with diaphragm-type, strain-gage pressure transducers. These transducers were calibrated with a deadweight pressure calibration apparatus, and periodic checks were conducted on each transducer and its corresponding millivolt recorder. Each of the transducers was referenced to atmosphere except for the cell pressure and the static pressure at the exit of the Mach 4 nozzle which were referenced to the pressure maintained by a vacuum pump. Estimates of the precision of the pressure measurements (psi) are tabulated below:

p_c	p_H	p_{o_H}	p_{o_c}	$p_{o_{NE}}$	p_1	p_2	p_3	p_4
±0.5	±3	±3	±0.7	±0.1	±1.0	±3	±0.1	±0.1

Temperatures were measured with copper-constantan, iron-constantan, or Chromel®-Alumel® thermocouples. Mixing chamber and test cell total temperatures were obtained with modified Rosemount 103-3X probes. No effective means was available for calibrating or checking thermocouple temperature measurements; however, significant errors within particular thermocouples could be noticed by referring to a duplicate set of couples in the immediate vicinity.

Estimates of the precision of the temperature measurements (°F) are tabulated below:

$T_{o_{NE}}$	T_{o_H}	T_{o_c}	T_2	T_3	T_5	T_6
±15	±15	±15	±15	±1.0	±15	±15

SECTION III
EXPERIMENTAL PROCEDURE

Three mixer configurations, identified in Fig. 6 as A, A-1, and B, were investigated. Temperature and pressure profiles were obtained in the aft section of the stilling chamber for configurations A and B and at 0.5 in. downstream of the Mach 4.0 nozzle for each of the three configurations. Additional data were recorded during each test run to monitor the mass flow, pressure, and temperature of both the primary and secondary flows. Equipment limitations would not permit operation at higher temperature, pressure, and mass flow ratio levels than presented herein.

The test apparatus was started by reducing the exhauster pressure to approximately 0.5 psi and initiating the primary and secondary flows. The heater was then energized to prevent the temperature of the heater elements from being reduced to below 760°R. As the heater temperature was increased, the primary and secondary airflows were increased simultaneously to prevent overheating of downstream test components.

Total temperature and pitot pressure profiles were recorded over a range of heater exit to mixing chamber pitot pressure ratios from 4.00 to 5.25 and secondary to primary mass flow ratios from 0.86 to 2.70. Successive steady-state data were recorded at points across the mixing chamber and at the nozzle exit by use of the traversing probes. Efforts were made to keep the primary and secondary airflow conditions from varying while successive data points were being recorded; however, this was not always achieved because of control limitations of the heater air supply system and because of the inherent characteristics of the heater itself.

SECTION IV
DISCUSSION AND RESULTS

Mixer performance at various operating conditions is presented in the form of pressure and temperature ratio profiles in the stilling chamber and at the exit of the Mach 4.0 nozzle. As previously mentioned, efforts to prevent the heater pressure and temperature from varying during a test run were not successful. Heater temperature and pressure varied as much as ±70°R and ±10 psi, respectively; however, the secondary flow conditions remained essentially constant. For all test runs the secondary flow temperature was approximately 470°R, and the secondary manifold pressure was approximately equal to the pressure in the mixer stilling chamber.

The temperature and pressure profiles for each configuration are presented in the form of the ratio of the traversing probe temperature to heater exit probe temperature (T_o/T_{oH}), and the ratio of the traversing probe pitot pressure to heater exit pitot pressure (p_o/p_{oH}). These data were recorded simultaneously and presented in this manner to eliminate the effects of heater instability.

4.1 CONFIGURATION A

Stilling chamber pressure and temperature profiles are presented in Figs. 7 and 8, respectively, for configuration A (60-deg secondary flow injection, L/D = 2.3). Separate test runs were required to obtain these data because of the single installation mount for either the pressure or temperature probe. Smooth profiles exist for both mass flow ratios, $\dot{m}_S/\dot{m}_P$, investigated. The mass flow ratio, $\dot{m}_S/\dot{m}_P$, of 2.57 assumed in the mixer analysis was not investigated during the pressure runs. However, Eqs. (I-1) and (I-2) presented in the Appendix were used to calculate the resulting pressure ratio, p_{oH}/p_{oc}, for the 2.70 mass flow test run. A comparison of the theoretical and experimental results is presented in Fig. 7. The close comparison of the results substantiate the use of Eqs. (I-1) and (I-2) for predicting the stilling chamber to primary pressure ratio, p_{oc}/p_{oH}.

The data in Fig. 8 show good mixing characteristics near the design secondary to primary mass flow ratio, $\dot{m}_S/\dot{m}_P$, of 2.57 to 1, even though the profiles were obtained at different levels of primary mass flow - 1.0 and 1.4 lb/sec. Additional temperature profiles recorded at off-design mass flow ratios down to 0.86 are presented. As the mass flow ratio, $\dot{m}_S/\dot{m}_P$, is decreased, a slight core begins to develop in the chamber. Hence, it may be assumed that the performance of the mixer depends on the mass flow ratio and not on the level of primary mass flow, which ranged from 0.99 to 1.5 lb/sec. The nonuniformity in the temperature profiles at the off-design mass flow ratios are shown later to diminish through the Mach 4.0 nozzle.

Velocities in the stilling chamber were calculated for each of the test runs presented in Fig. 8 and are tabulated below. The velocities were calculated using average values of recorded data for each test run.

MIXING CHAMBER VELOCITIES

$\dot{m}_S/\dot{m}_P$	$\dot{m}_P$, lb/sec	T_{oc}, °R	p_c, psia	V, ft/sec
0.86	1.43	1139	38.3	54.0
1.41	1.39	1010	49.2	47.0
1.76	1.44	950	56.0	45.8
2.57	1.00	768	50.0	37.2
2.63	1.40	830	70.0	40.6

Pressure and temperature profiles recorded at the exit of the Mach 4.0 nozzle for configuration A are presented in Figs. 9 and 10, respectively. These data were obtained simultaneously using a manually operated dual probe. Data were recorded at the design mass flow ratio, $\dot{m}_s/\dot{m}_p$, of 2.57 and at off-design ratios down to 1.31. The transverse pressure profiles in Figs. 9a and b show a variation of ±1.25 percent for the design ratio and ±2.6 percent for the off-design ratios. Temperature profiles, Figs. 10a and b, show a variation of ±0.89 to ±1.1 percent for the design mass flow ratio and of ±0.4 to ±2.65 percent for off-design ratios. These variations are calculated using only the flat portion of the profile excluding the boundary layer near the nozzle wall. The estimated boundary-layer thickness at the nozzle exit is 1.0 to 1.25 in.

4.2 CONFIGURATION A-1

Results obtained with configuration A-1 (60-deg secondary injection without constant diameter section, L/D = 1.7) are presented in Figs. 11 and 12. Only pressure and temperature profiles at the exit of the Mach 4.0 nozzle were obtained, since the probe for measuring the stilling chamber profiles was removed with the constant diameter section. Tests were made at and near the design mass flow ratio, $\dot{m}_s/\dot{m}_p$, of 2.57 and at off-design ratios down to 1.33. Comparison with results of configuration A (Figs. 9 and 10) shows very little change in nozzle exit profiles except for a slight thickening of the boundary layer. Variations of ±1.3 to ±2.44 percent were recorded for pressure and of ±1.32 to ±2.26 percent for temperature. There were no adverse control effects of primary and secondary air systems encountered during these tests.

4.3 CONFIGURATION B

Configuration B (45-deg secondary injection, L/D = 2.3) results are presented in Figs. 13, 14, and 15. Mixing chamber pressure profiles are presented in Fig. 13. Comparison of these results with those obtained with configuration A (Fig. 7) shows that a slight pressure core developed in the chamber for all mass flow ratios investigated. Since the intersection of the injected flow centerlines with the chamber centerline for configuration B was 0.60 in. closer to the choked nozzle throat, the shock pattern of the primary flow may not have broken down sufficiently to permit required penetration. Also, the analysis of the system presented in the Appendix shows that the depth of penetration is related to the secondary to primary momentum ratio; hence, a larger momentum ratio may have been required for centerline penetration since the penetration distance to the mixer centerline is longer for configuration B than for configuration A.

An unstable mixing process was experienced during tests with configuration B. Continuous manipulation of the supply pressure of both the primary and secondary flows was required to keep the total mass flow constant. This also could have been caused by the fact that the injected flow centerline intersection for configuration B was closer to the choked nozzle throat than for configuration A. Hence, the instabilities of the shock system would be more strongly felt. Stilling chamber temperature profiles were not obtained for configuration B; however, both pressure and temperature profiles were recorded at the Mach 4.0 nozzle exit and are presented in Figs. 14 and 15, respectively.

Comparison of pressure profiles of configuration B with those of configuration A (Fig. 9) shows a more unsymmetrical profile with slight increases and decreases across the expected flat portion. Variation of ±2.41 to ±5.3 percent resulted through the range of mass flow ratios investigated (1.33 to 2.62). Variation of temperature profiles ranged from ±0.54 percent at the design mass flow ratio of 2.57 to ±3.8 percent for off-design ratios.

SECTION V
CONCLUSIONS

The experimental investigation of a mixing chamber employing upstream injection in conjunction with a Mach 4.0 nozzle leads to the following conclusions:

1. A relatively short mixer, L/D = 2.3, employing the upstream injection concept can be designed to produce pressure and temperature profiles at the nozzle exit of not more than a ±5-percent variation.
2. The mixer configuration with L/D = 2.3 and the injection angle equal to 60 deg produced uniform pressure and temperature profiles both at the chamber and at the exit of the Mach 4.0 nozzle for the design mass flow, $\dot{m}_S/\dot{m}_P$, and pressure, p_{o_H}/p_{o_C}, ratios.
3. No significant differences were obtained in the nozzle exit pressure and temperature profiles for the two mixing chamber configurations, L/D = 2.3 and 1.7 with 60-deg injection. Mixing chamber profiles were not recorded for the L/D = 1.7 configuration. However, indications are that the mixer performed satisfactorily without the constant-area section.

4. Considerable control difficulty in holding the total mass flow constant was experienced during tests of the configuration with the injection angle equal to 45 deg. Recorded profiles in the mixing chamber revealed a slight core, indicating that the primary flow had not been penetrated; however, profiles obtained at the Mach 4.0 nozzle exit show that the core diminished during passage through the Mach 4.0 nozzle.

5. Pressure level in the mixing chamber can be controlled and predicted by correctly sizing the choked nozzle throat with respect to the downstream or tunnel nozzle throat area.

APPENDIX
ANALYSIS OF MIXING CHAMBER

The basic equation for operation and sizing of the mixer, as determined by considering the ratio of the critical weight flow through the choked nozzle to that through the expansion nozzle, is

$$\frac{\dot{m}_p}{\dot{m}_c} = \frac{p_{o_H}}{p_{o_c}} \cdot \frac{A_*}{A_{**}} \cdot \sqrt{\frac{T_{o_c}}{T_{o_H}}} \cdot \frac{K_p}{K_c} \qquad \text{(I-1)}$$

where

$$\dot{m}_c = \dot{m}_p + \dot{m}_s.$$

The stilling chamber temperature in Eq. (I-1) was determined by performing an enthalpy balance in the mixing zone with the equation

$$T_{o_c} = \frac{\dot{m}_p \, T_{o_H} + \dot{m}_s \, T_{o_s}}{\dot{m}_c} \qquad \text{(I-2)}$$

assuming C_p = constant.

The throat area ratio of the choked nozzle section to the Mach 4.0 expansion nozzle is 0.093. Using assumed values of 0.28 and 0.397 for the mass flow and temperature ratios, respectively, yields a stagnation pressure ratio of 4.78. To insure that velocities in the stilling chamber were suitably low to support mixing (50 to 75 ft/sec), a stilling chamber to expansion nozzle throat area ratio of approximately twenty was chosen. An expansion angle of 30 deg in the mixing chamber was found to suit the geometric layout of the mixer since a stilling chamber length of about 6 in. was desired and an overall mixer length of about 2.5 times the stilling chamber diameter was a test objective.

Upstream injection angles of 45 and 60 deg with respect to mixer centerline were chosen, and the centerline of the secondary stream was made to intersect the centerline of the primary stream at approximately seven and eight throat diameters downstream from the choked nozzle minimum area. The static pressure in the chamber at the injection ports was determined by the equation

$$\frac{p_c}{p_x} = \frac{\dot{m}_c}{\dot{m}_x} \cdot \frac{A_x}{A_c} \cdot \frac{M_x}{M_c} \cdot \sqrt{\frac{T_c}{T_x}} \qquad \text{(Ref. 3) (I-3)}$$

where T_c was assumed to be equal to T_x, and M_x was determined from the equation for frictionless, one-dimensional flow with only area change considered. Reference 3 states this equation as

$$\frac{A_x}{A_c} = \frac{\dfrac{1}{M_x}\sqrt{\left[\dfrac{2\left(1 + \dfrac{\gamma - 1}{2} M_x^2\right)}{\gamma + 1}\right]^{\frac{\gamma + 1}{\gamma - 1}}}}{\dfrac{1}{M_c}\sqrt{\left[\dfrac{2\left(1 + \dfrac{\gamma - 1}{2} M_c^2\right)}{\gamma + 1}\right]^{\frac{\gamma + 1}{\gamma - 1}}}} \tag{I-4}$$

The stilling chamber Mach number, M_C, was considered to be 0.05 for the analysis. It can be shown by these equations that the static pressure in the chamber at the injection station, and hence in the bypass manifold, was nearly equal to the stagnation pressure in the mixer stilling chamber. The injection ports were sized by considering the investigation of Hawthorne, et al. (Ref. 4). Hawthorne found for transverse injection of a cold stream into a hot stream that penetration per duct depth depended on the factor

$$\frac{\text{Momentum Ratio } \left(\frac{\text{cold}}{\text{hot}}\right)}{\left[1 + \frac{\pi}{4}\left(\frac{d_i^2}{d^2}\right) \frac{V_c}{V_H}\right]^2}$$

Since transverse injection was not used and because the design secondary to primary mass flow ratios in this experiment were much larger than those of Ref. 4, this factor was used only as an indication of the amount of penetration. Reference 4 indicated that for half-depth penetration or better, the penetration factor should be a minimum of 0.30. Considering this factor, the bypass holes were chosen to be 0.75 in. in diameter.

Information in Refs. 5 and 6 indicates that the normal shock analogy which was used for analysis of the mixer may not apply in the analysis of the choked nozzle. Instead, it is suggested that an oblique shock system exists in the choked nozzle as a result of a shock-induced boundary-layer separation.

REFERENCES

1. Cresci, R. J. "Tabulation of Coordinates for Hypersonic Axisymmetric Nozzles, Part I: Analysis and Coordinates for Test Section Mach Numbers of 8, 12, and 20." WADC-TN-58-300 (AD 204213), October 1958.

2. Sivells, J. C. and Payne, R. G. "A Method of Calculating Turbulent-Boundary-Layer Growth at Hypersonic Mach Numbers." AEDC-TR-59-3 (AD 208774), February 1959.

3. Shapiro, Ascher H. The Dynamics and Thermodynamics of Compressible Fluid Flow, Vols. I and II. The Ronald Press Company, New York, 1953.

4. Hawthorne, et al. "The Penetration of a Jet of Cold Air into a Hot Stream." Technical Note No. Eng 271, Royal Aircraft Establishment, Farnborough, March 1944.

5. Arens, M. and Spiegler, E. "Shock-Induced Boundary Layer Separation in Overexpanded Conical Exhaust Nozzles." AIAA Journal, Vol. 3, March 1963, pp. 578-581

6. Page, R. H. "Flow Separation in Nozzles." Journal of Aerospace Sciences, Vol. 29, January 1962, pp. 110-111.

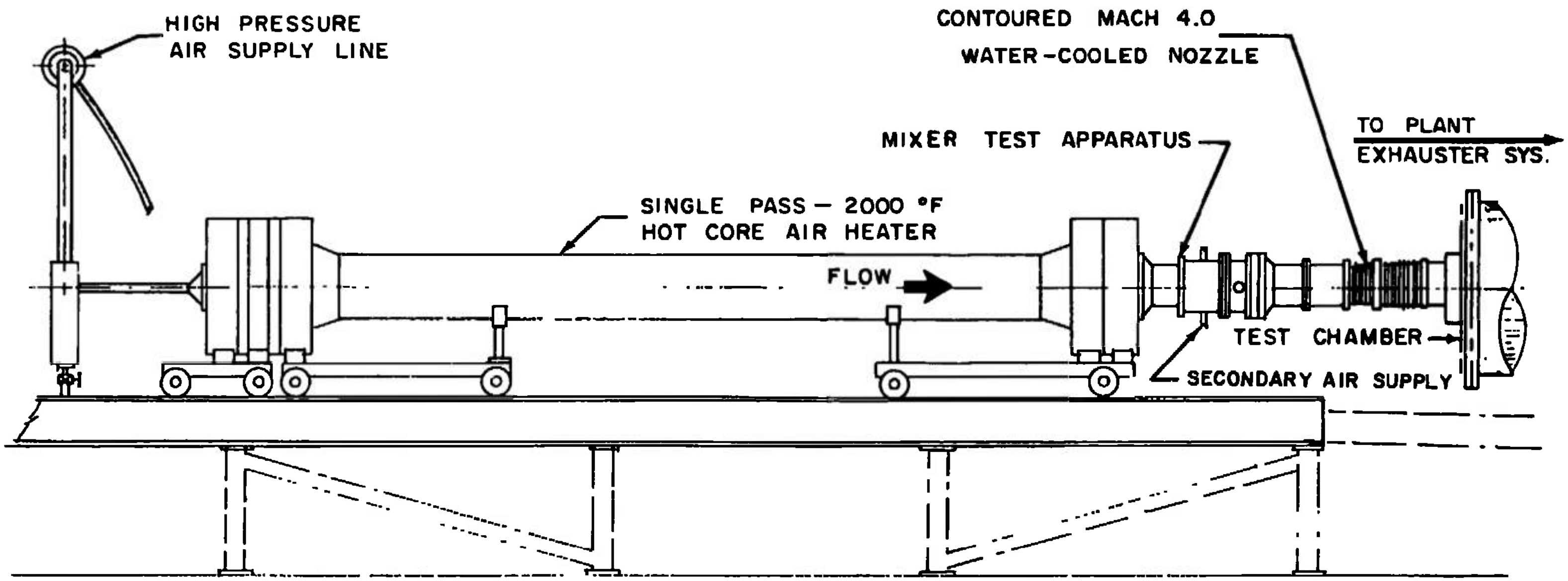
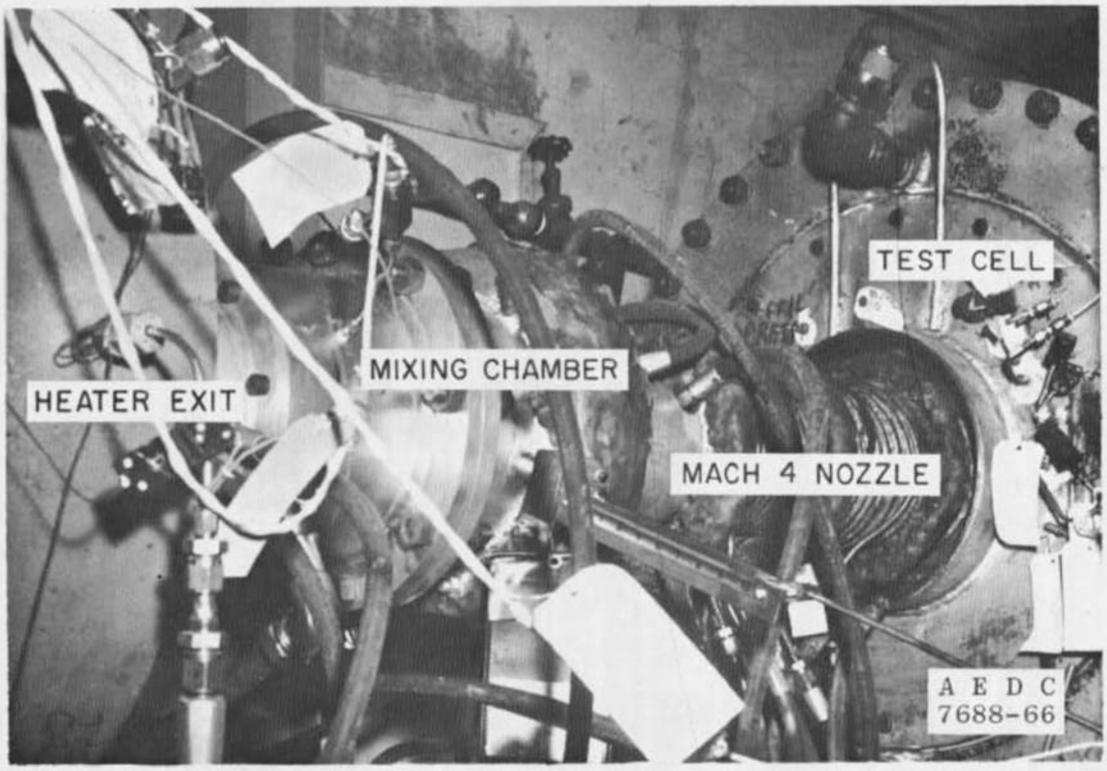
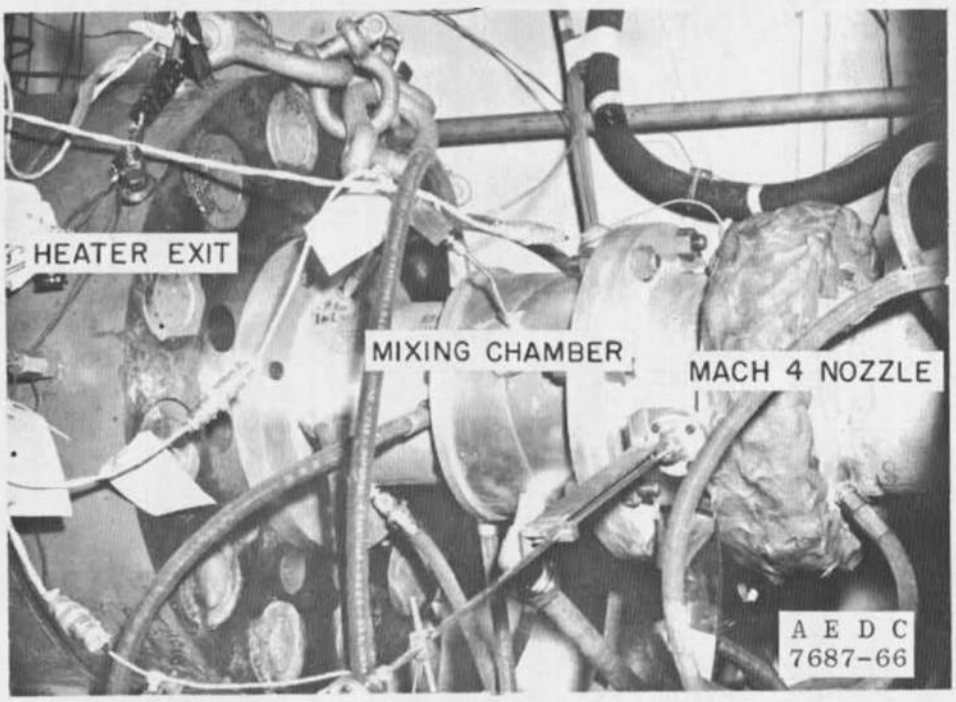


Fig. 1 Illustration of Test Components

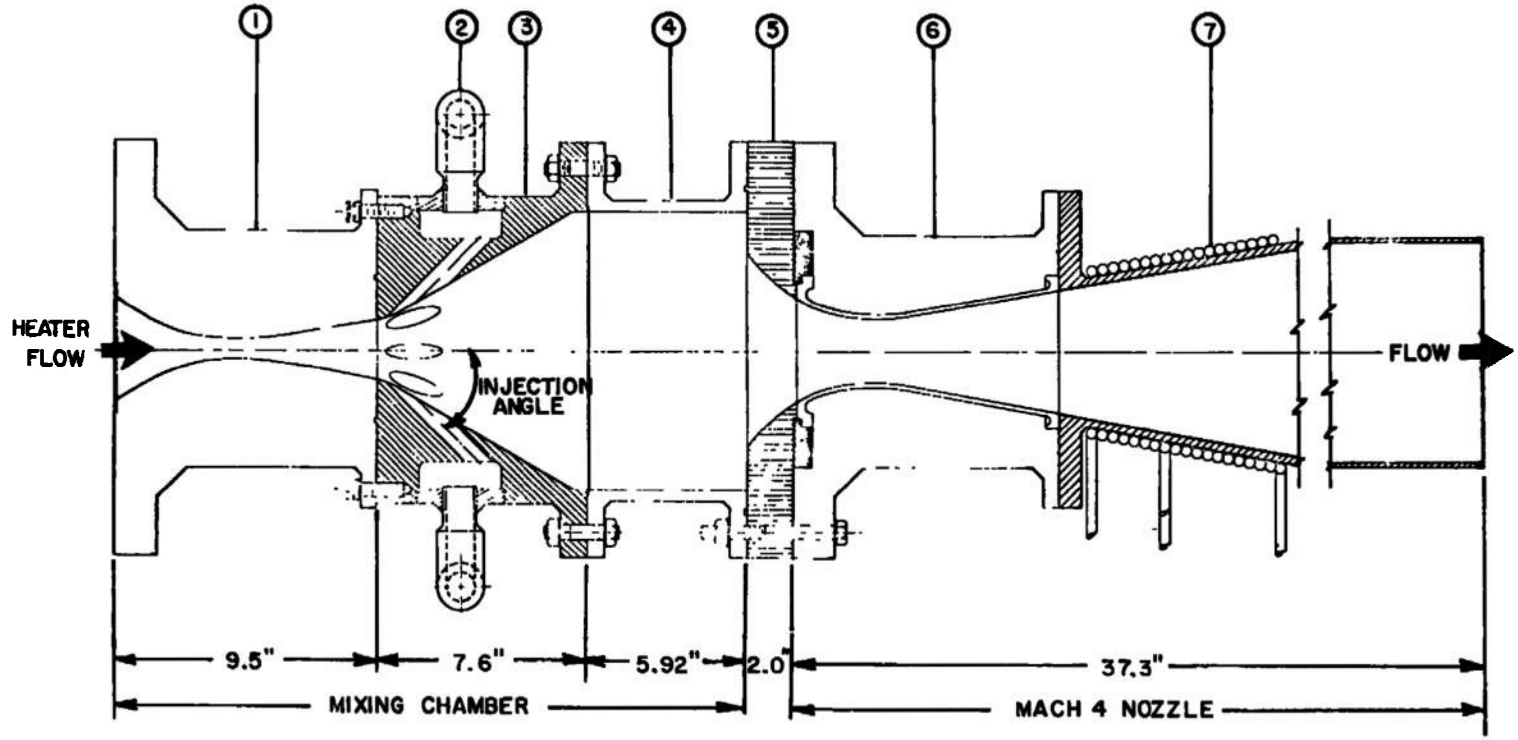


a. Tunnel Installation



b. Mixer Installation

Fig. 2 Wind Tunnel Installation



1. CHOKE NOZZLE

THROAT DIAM	0.694"
LENGTH - THROAT TO EXIT	5.0"
EXIT DIAM	2.2"

2. SECONDARY INJECTION

INJECTION ANGLE, CONFIG	A = 60°
INJECTION ANGLE, CONFIG	B = 45°
INSIDE DIAM OF INJECTION PORTS	= .75"
NUMBER OF INJECTION PORTS	= 8

3. EXPANSION SECTION

ENTRANCE DIAM	2.2"
EXPANSION ANGLE	30°
EXIT DIAM	10.02"

4. STILLING CHAMBER

DIAM	10.02"

5. MACH 4.0 NOZZLE ADAPTER

ENTRANCE DIAM	7.0"
EXIT DIAM	3.74"

6. MACH 4.0 NOZZLE

ENTRANCE DIAM	3.74"
THROAT DIAM	2.277"
EXIT DIAM	8.0"

7. BACKSIDE COOLING COILS

Fig. 3 Mixing Chamber and Mach 4.0 Nozzle Dimensions

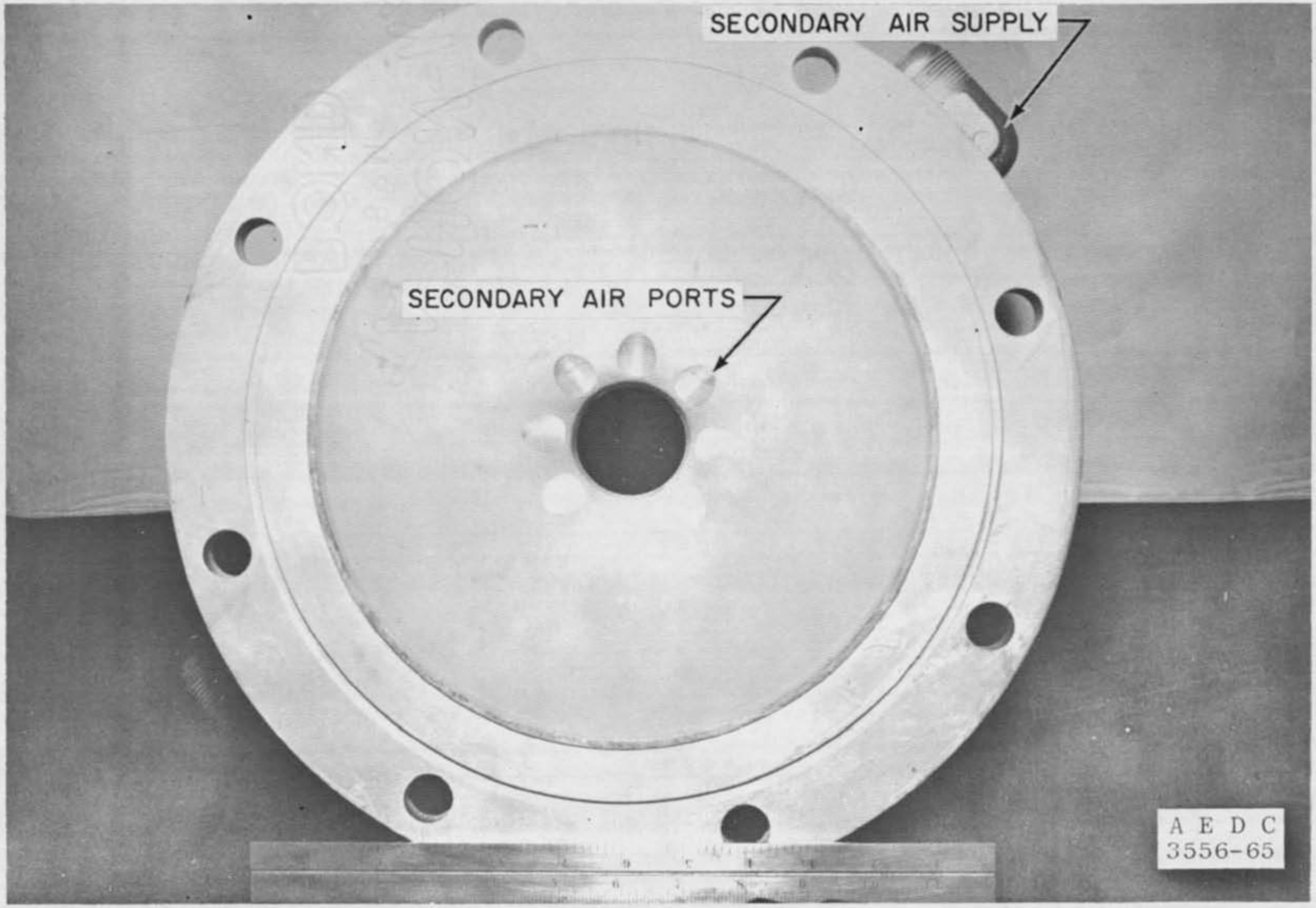


Fig. 4 Mixer Expansion Section, 60–deg Secondary Air Ports

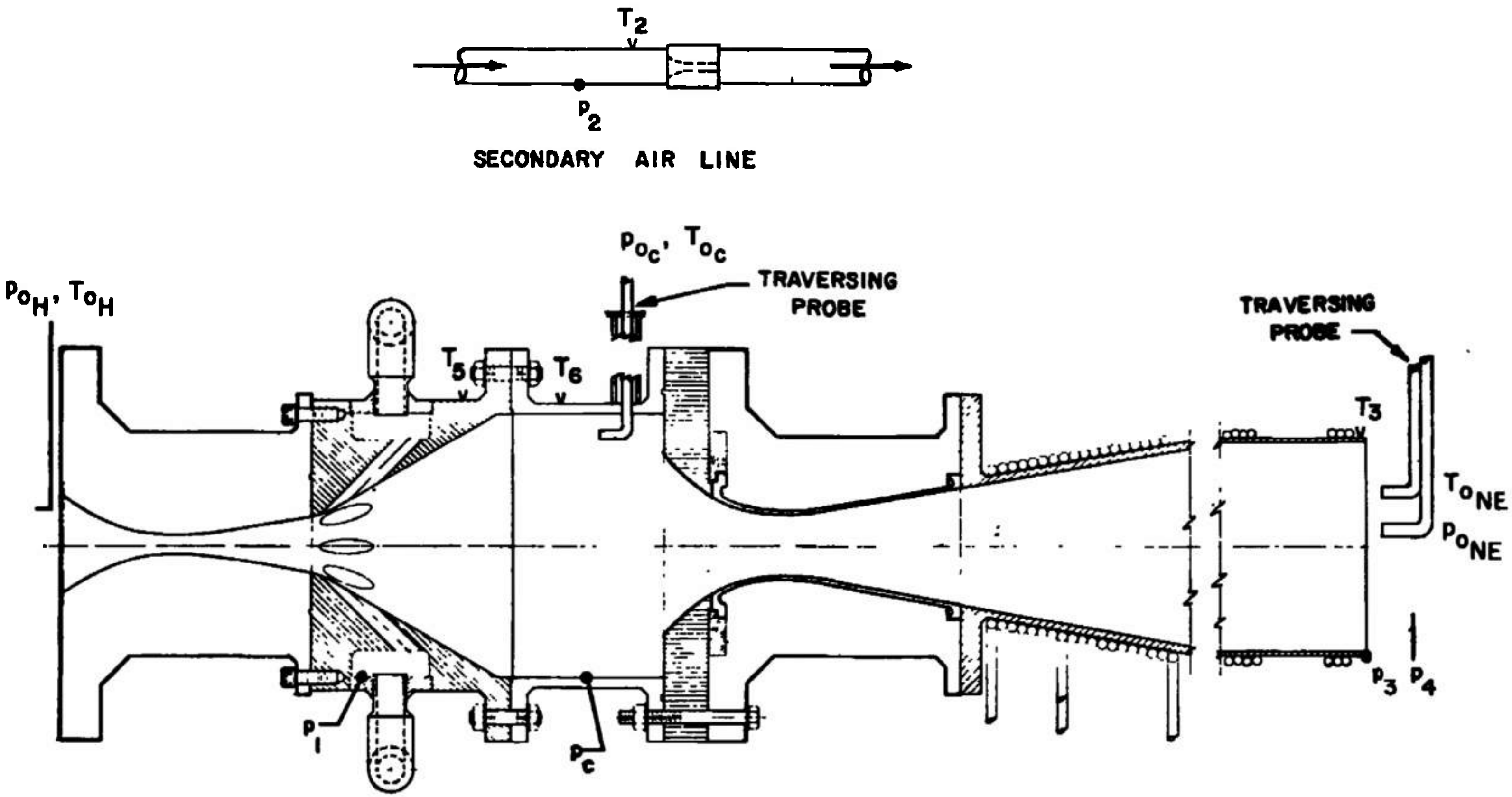
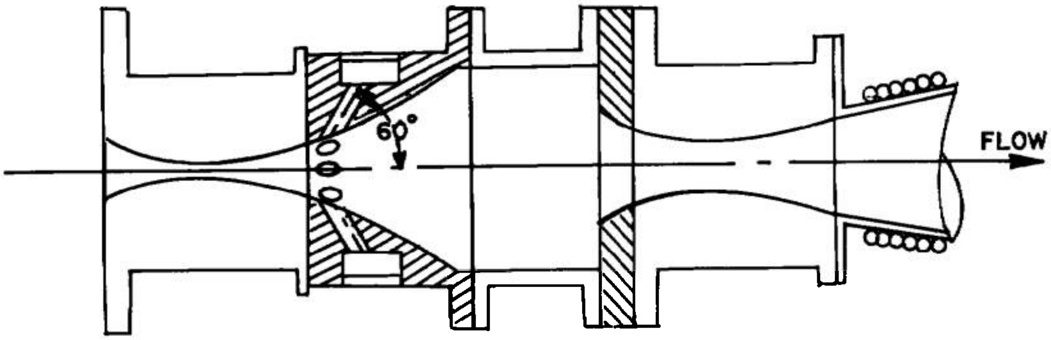
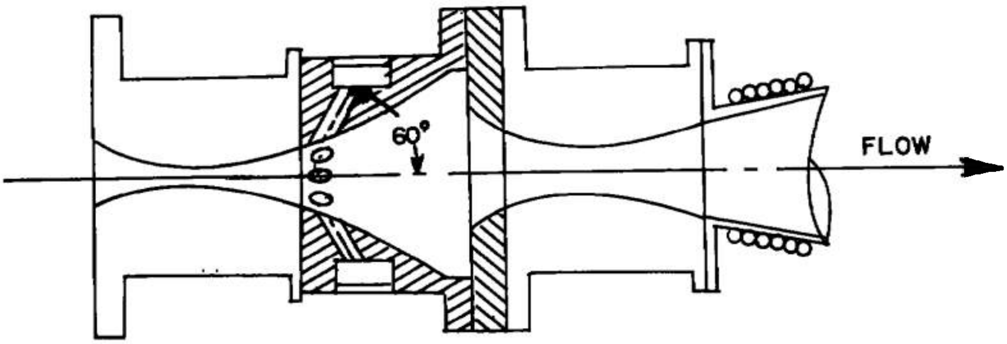


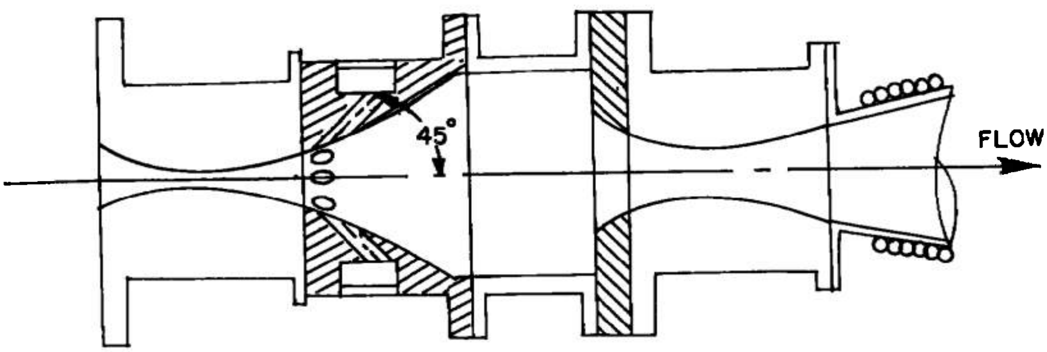
Fig. 5 Instrumentation Locations



CONFIGURATION A (L/D = 2.3)

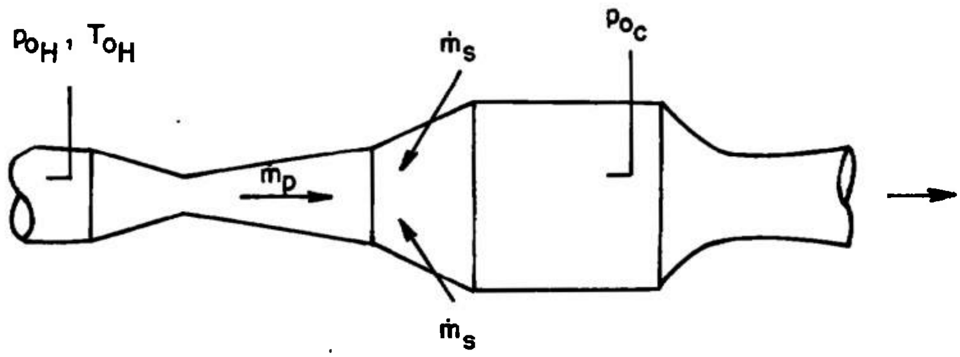


CONFIGURATION A - I (L/D = I.7)



CONFIGURATION B (L/D = 2.3)

Fig. 6 Mixer Test Configurations



SYM	$\dot{m}_s/\dot{m}_p$	p_{o_H}, psia (avg)	T_{o_H}, °R (avg)
O	2.70	200	1735
□	2.14	265	2120
---	2.70	EQS. (I-1 and I-2)	

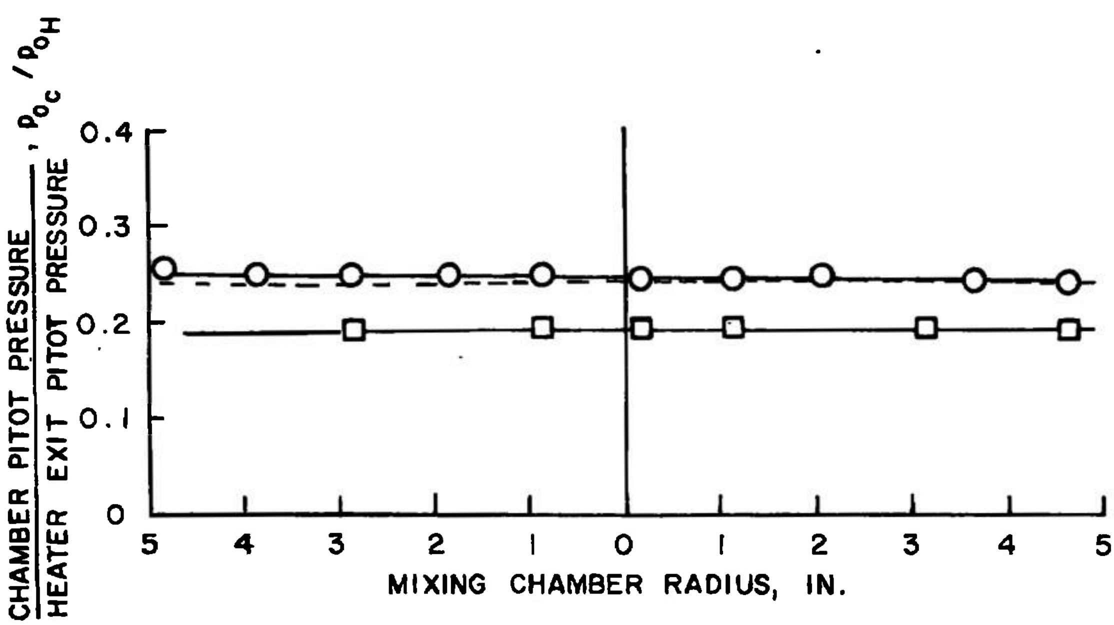
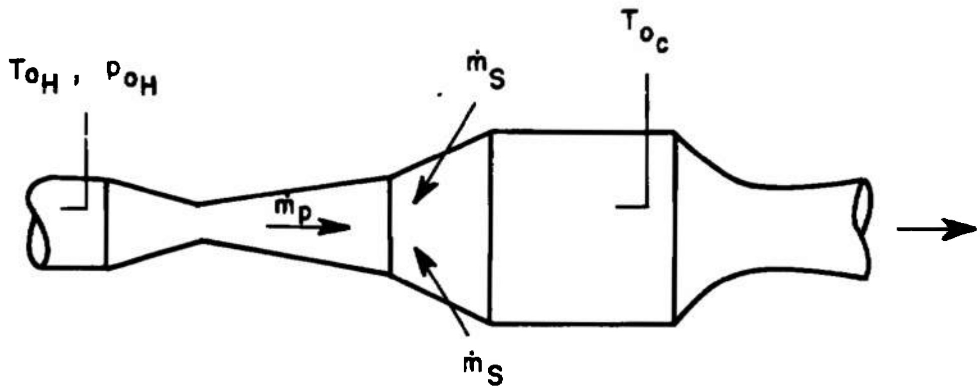


Fig. 7 Mixing Chamber Pressure Profiles, Configuration A



SYM	$\dot{m}_s/\dot{m}_p$	$\dot{m}_p$,lb/sec (avg)	T_{o_H},°R (avg)	p_{o_H},psia (avg)
○	0.86	1.43	1800	310
◇	1.41	1.39	1800	308
◇	1.76	1.44	1780	310
□	2.57	1.00	1790	200
○	2.63	1.40	1840	307

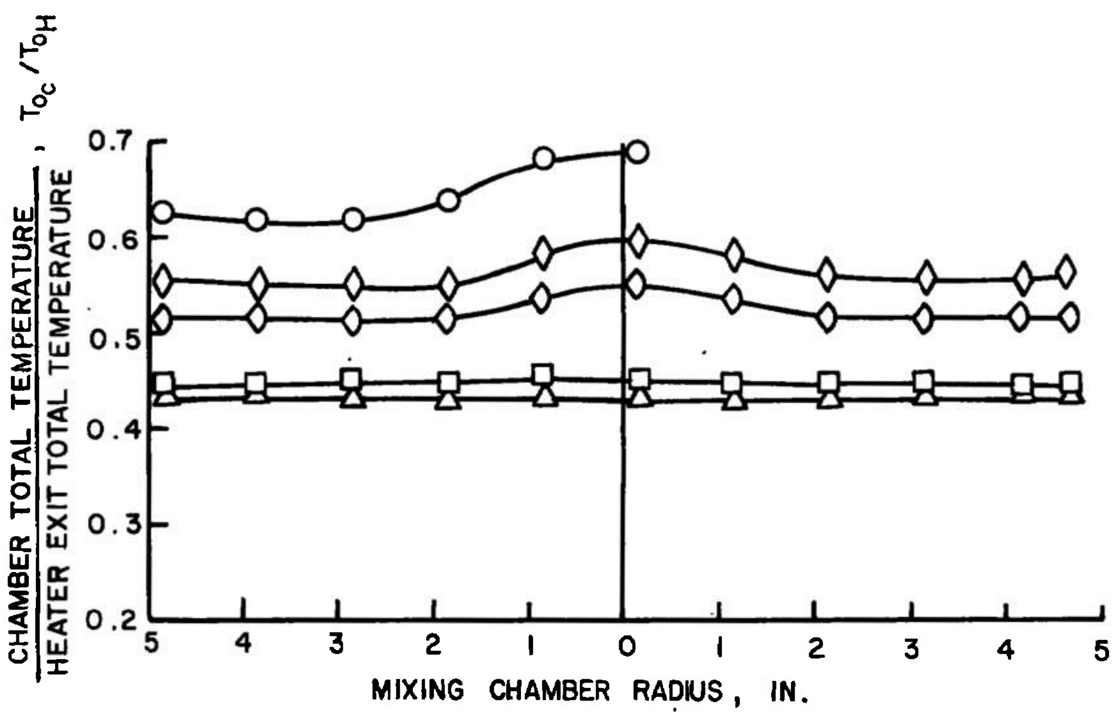
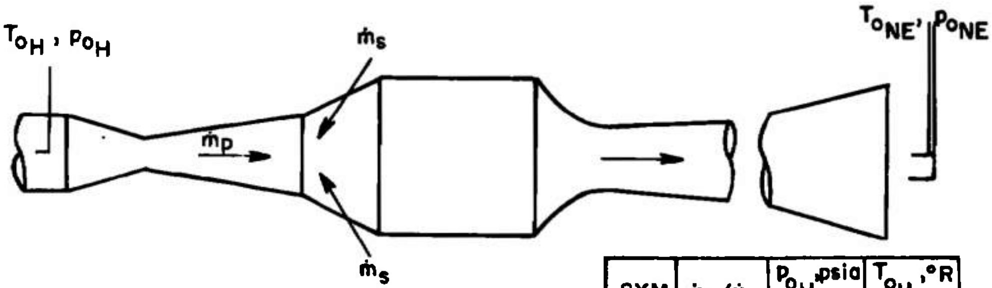
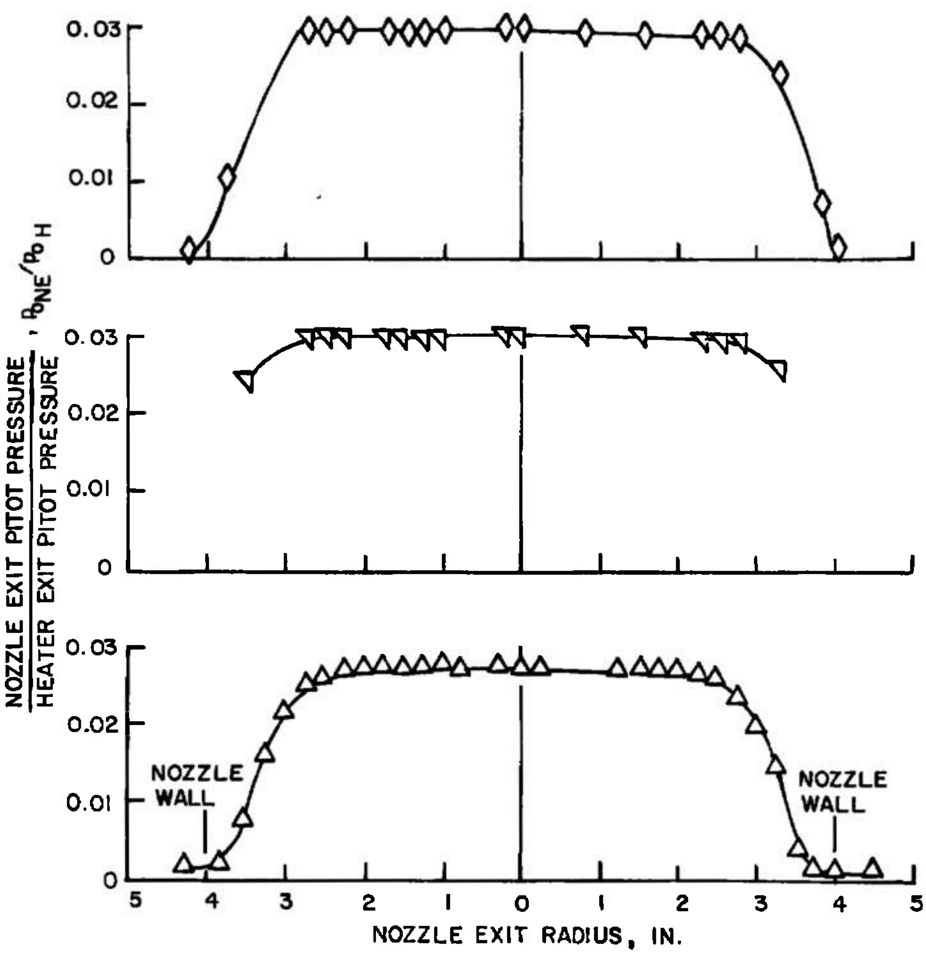


Fig. 8 Mixing Chamber Temperature Profiles, Configuration A

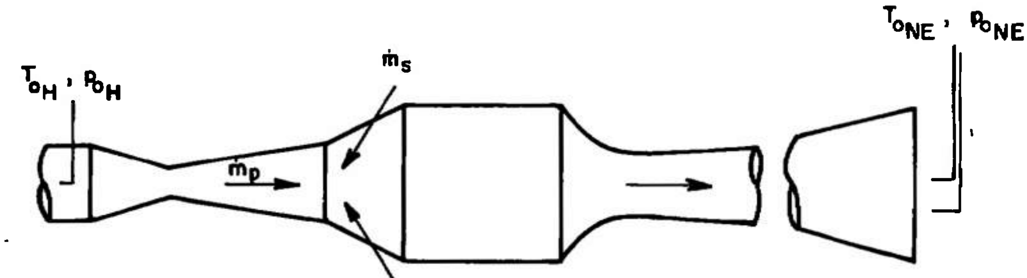


SYM	$\dot{m}_s/\dot{m}_p$	p_{o_H}, psia (avg)	T_{o_H}, °R (avg)
◊	2.57	339	2060
▽	2.57	206	1730
△	2.57	245	1910

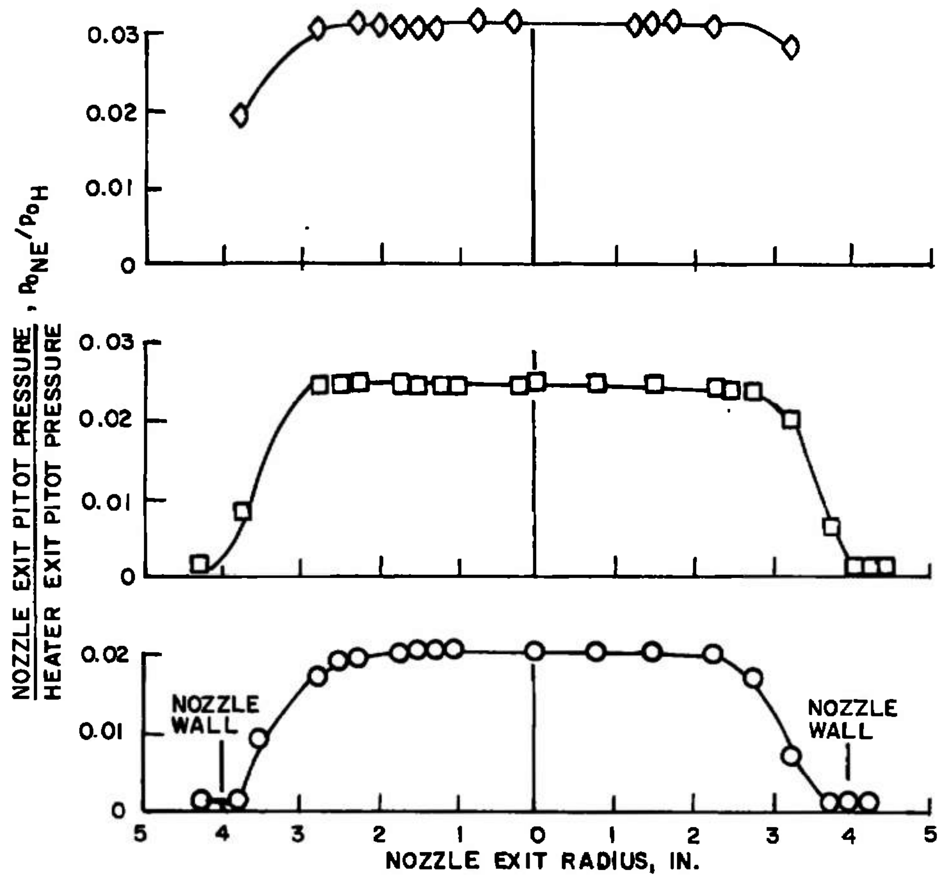


a. Effects of Varying Primary Mass Flow

Fig. 9 Mach 4.0 Nozzle Exit Pressure Profiles, Configuration A

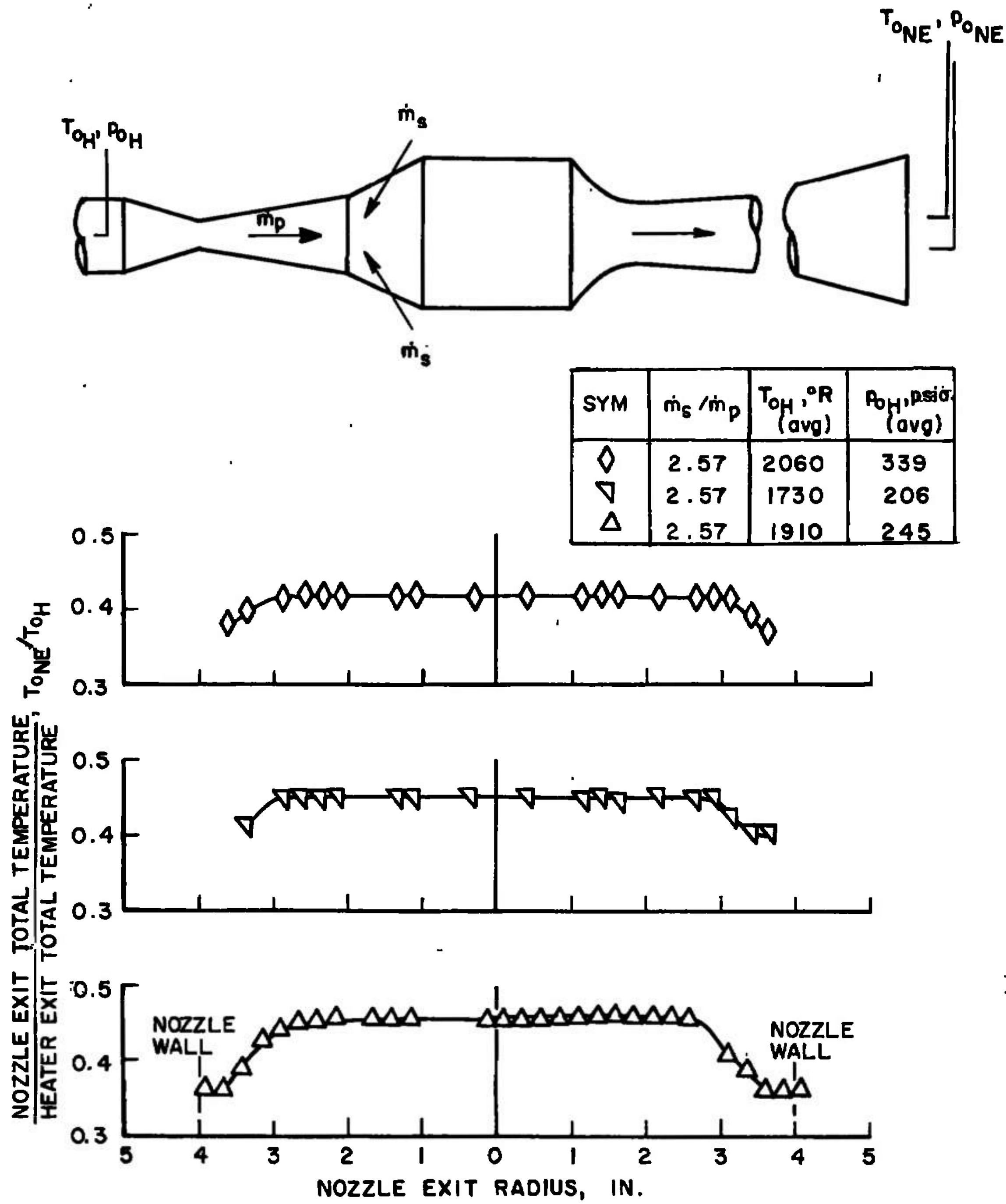


SYM	$\dot{m}_s/\dot{m}_p$	p_{o_H}, psia (avg)	T_{o_H}, °R (avg)
◇	2.16	250	1910
□	1.83	338	2040
○	1.31	340	1910



b. Effects of Varying Mass Flow Ratio

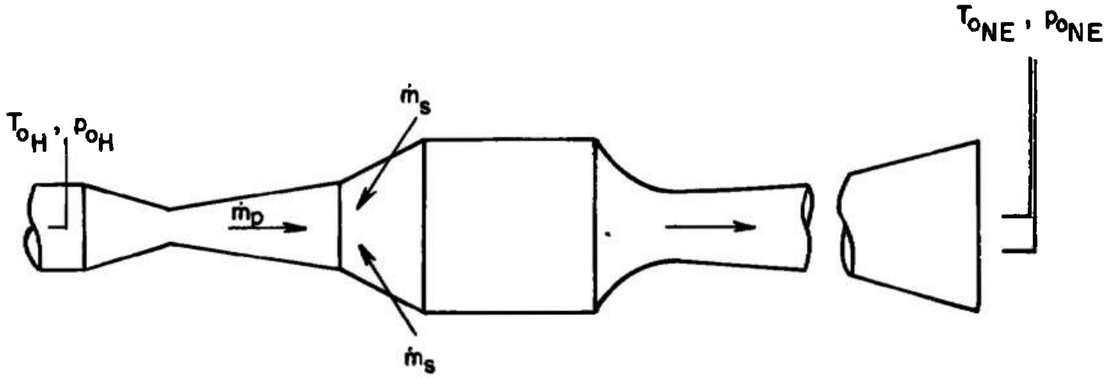
Fig. 9 Concluded



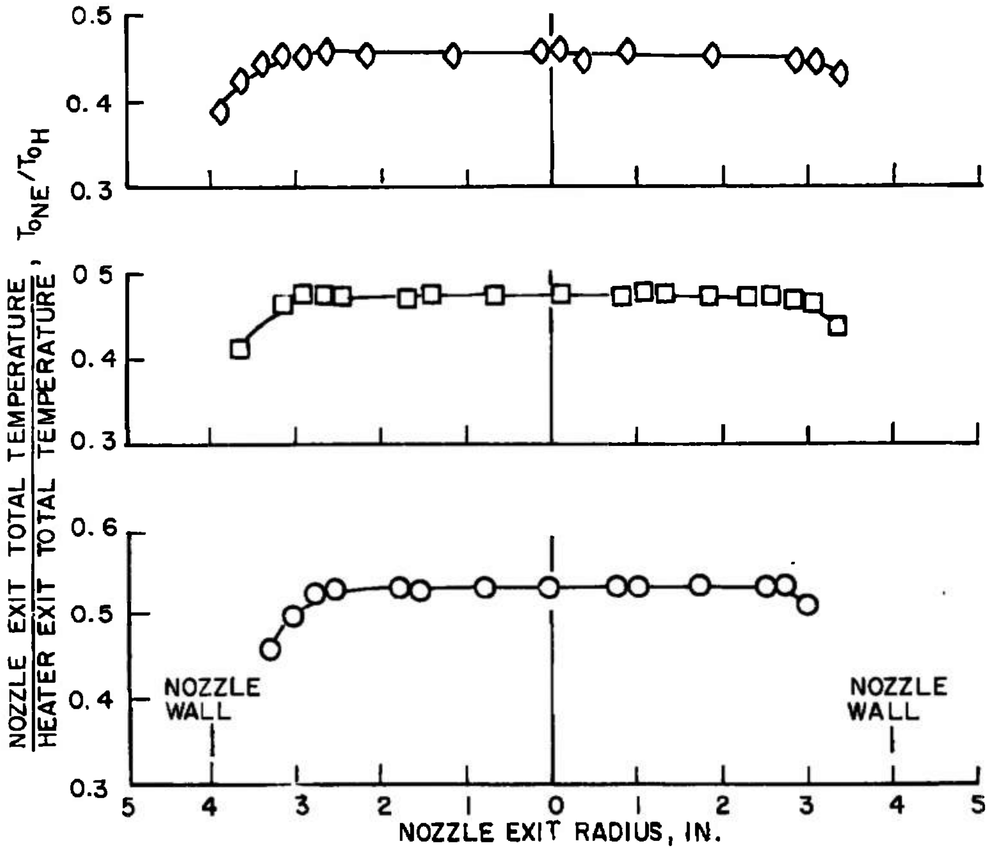
SYM	$\dot{m}_s/\dot{m}_p$	T_{o_H}, °R (avg)	p_{o_H}, psia (avg)
◊	2.57	2060	339
▽	2.57	1730	206
△	2.57	1910	245

a. Effects of Varying Primary Mass Flow

Fig. 10 Mach 4.0 Nozzle Exit Temperature Profiles, Configuration A

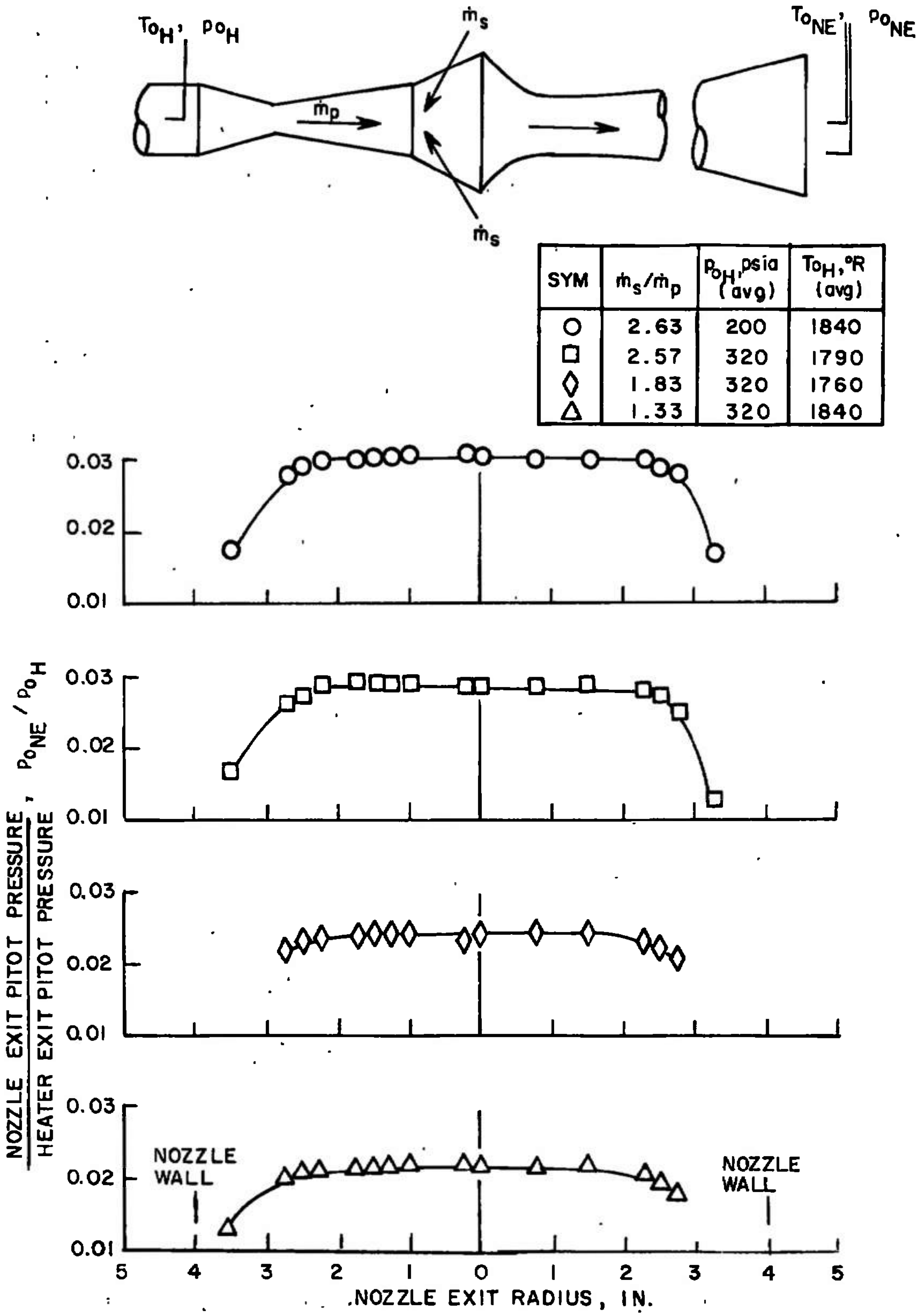


SYM	$\dot{m}_s / \dot{m}_p$	T_{oH}, °R (avg)	p_{oH}, psia (avg)
◇	2.16	1910	250
□	1.83	2040	338
○	1.31	1920	340



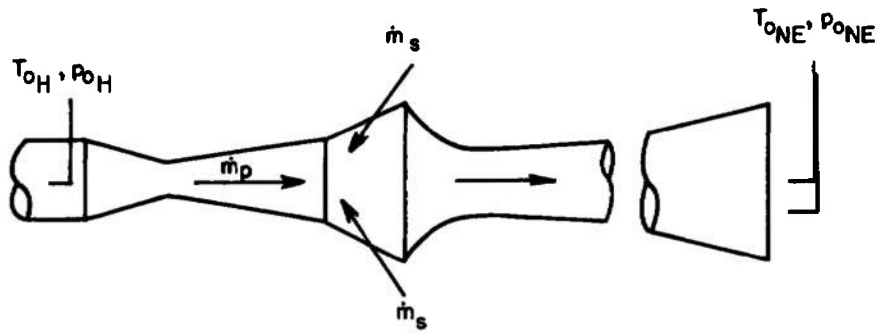
b. Effects of Varying Mass Flow Ratio

Fig. 10 Concluded



SYM	$\dot{m}_s/\dot{m}_p$	p_{o_H}, psia (avg)	T_{o_H}, °R (avg)
○	2.63	200	1840
□	2.57	320	1790
◇	1.83	320	1760
△	1.33	320	1840

Fig. 11 Mach 4.0 Nozzle Exit Pressure Profiles, Configuration A-1



SYM	$\dot{m}_s / \dot{m}_p$	T_{o_H}, °R (avg)	p_{o_H}, psia (avg)
○	2.63	1840	200
□	2.57	1790	320
◇	1.83	1760	320
△	1.33	1740	320

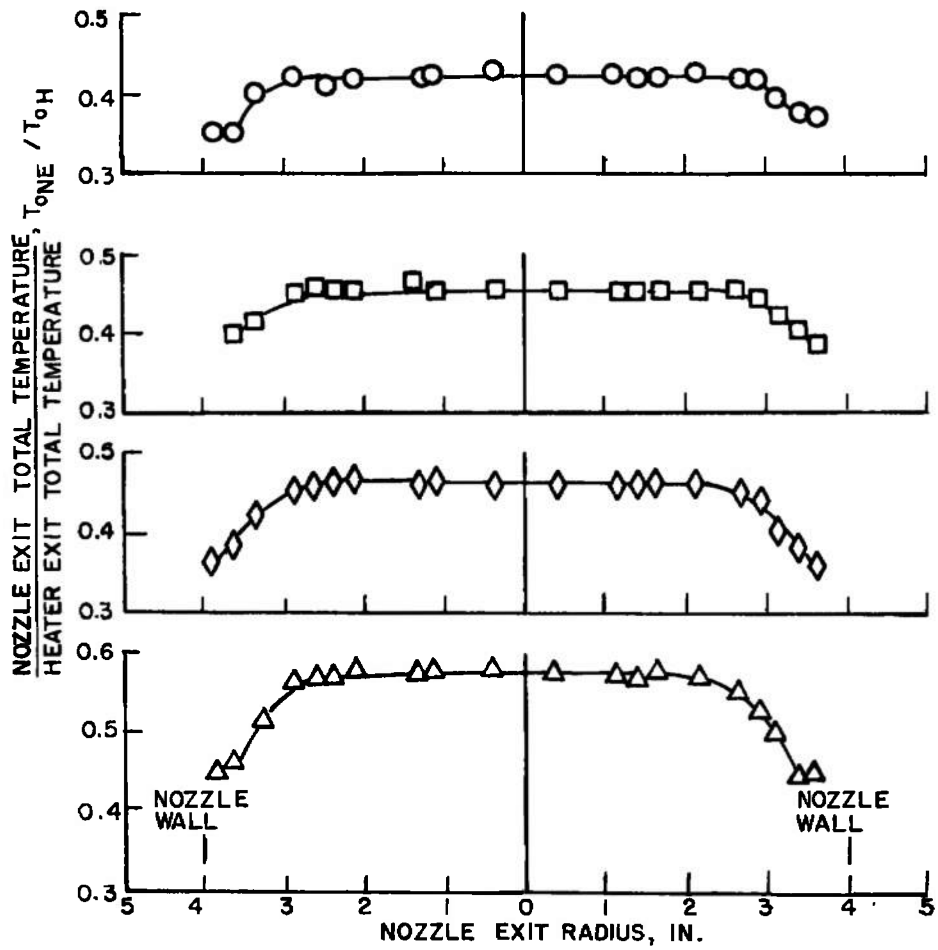
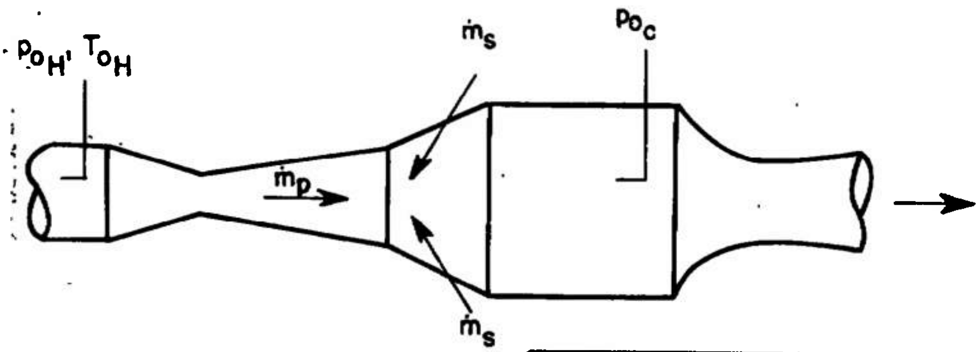


Fig. 12 Mach 4.0 Nozzle Exit Temperature Profiles, Configuration A-1



SYM	$\dot{m}_s / \dot{m}_p$	p_{o_H}, psia (avg)	T_{o_H}, °R (avg)
○	2.60	200	1860
□	2.56	325	1800
◊	1.67	320	1780
△	1.32	320	1790

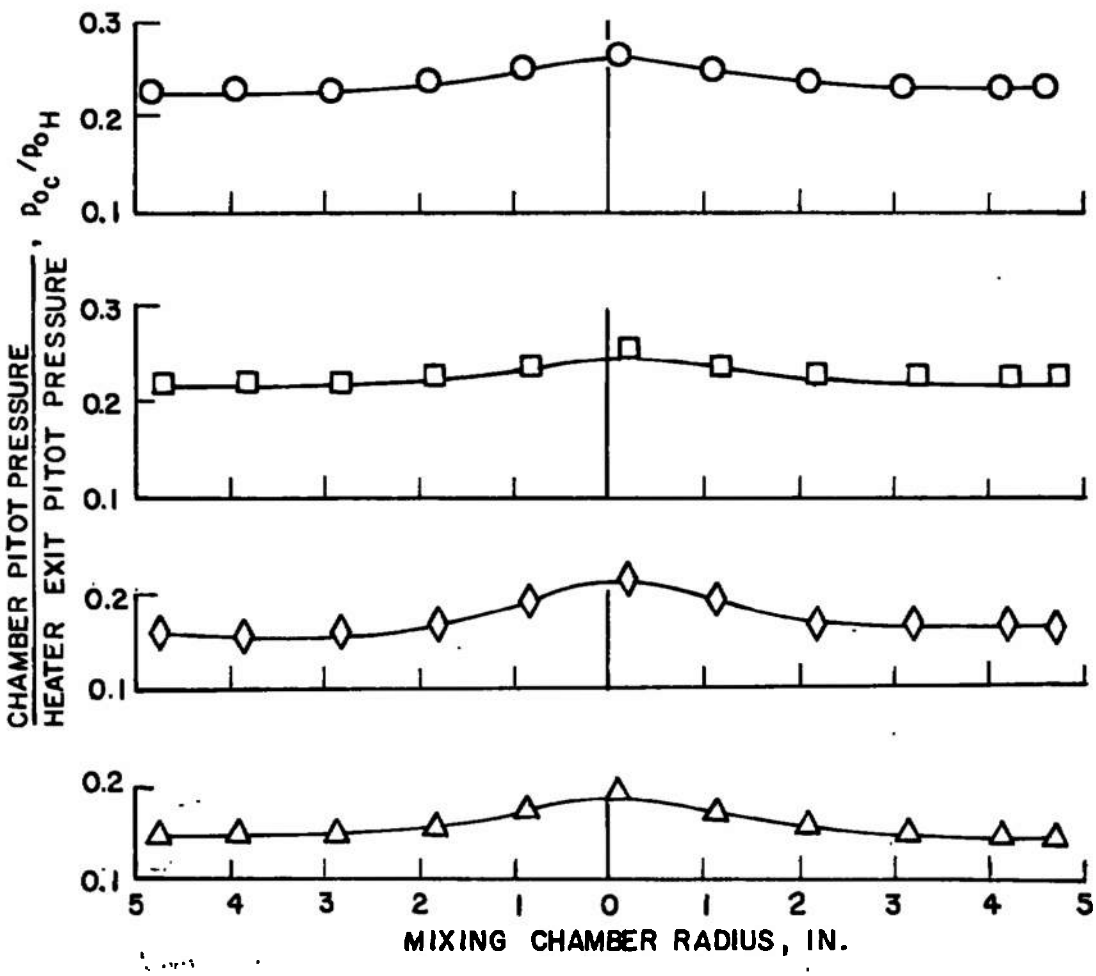
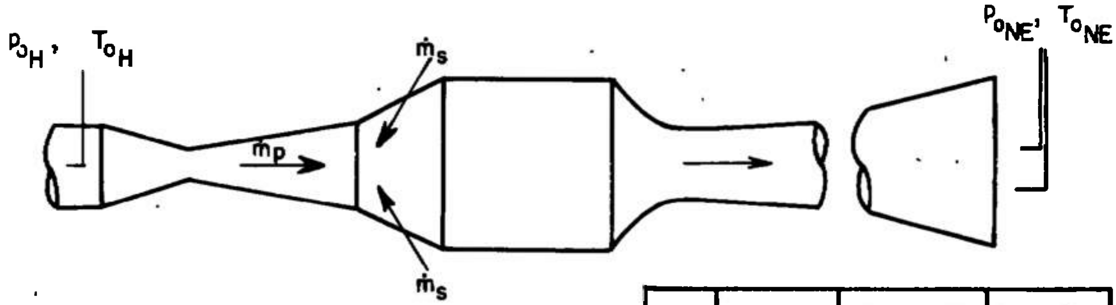


Fig. 13 Mixing Chamber Pressure Profiles, Configuration B



SYM	$\dot{m}_s/\dot{m}_p$	p_{o_H}, psia (avg)	T_{o_H}, °R (avg)
○	2.62	200	1870
□	2.57	325	1830
◇	1.75	327	1760
△	1.33	322	1780

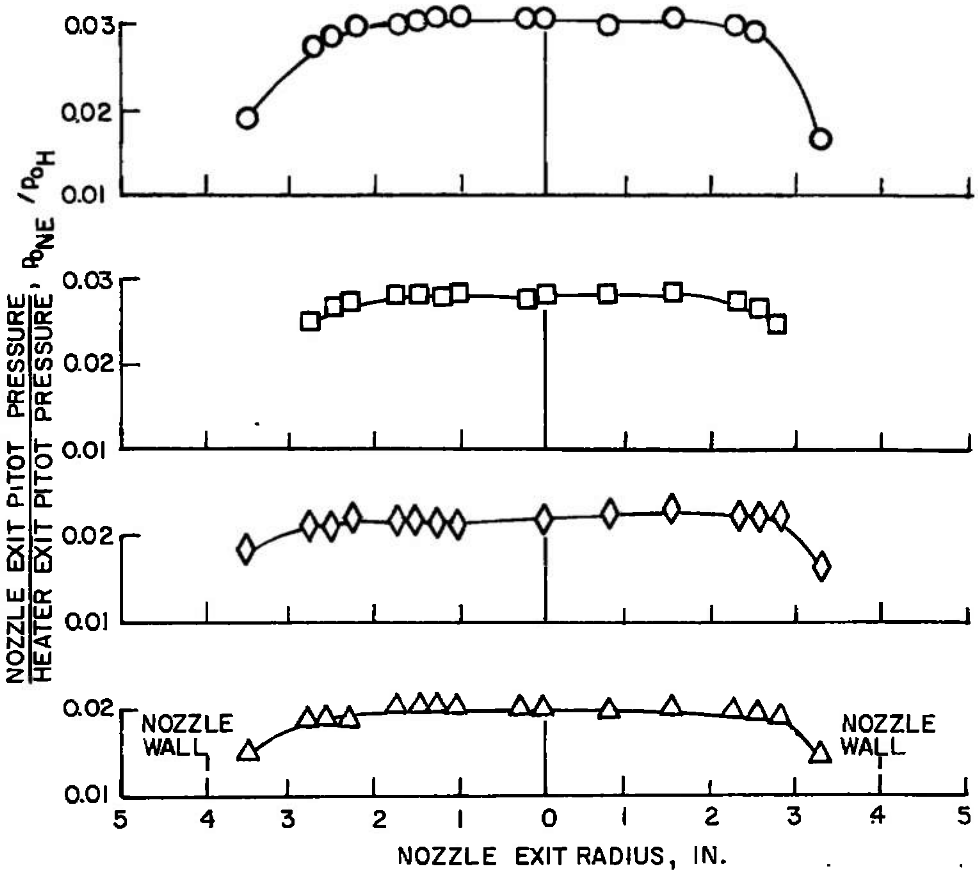
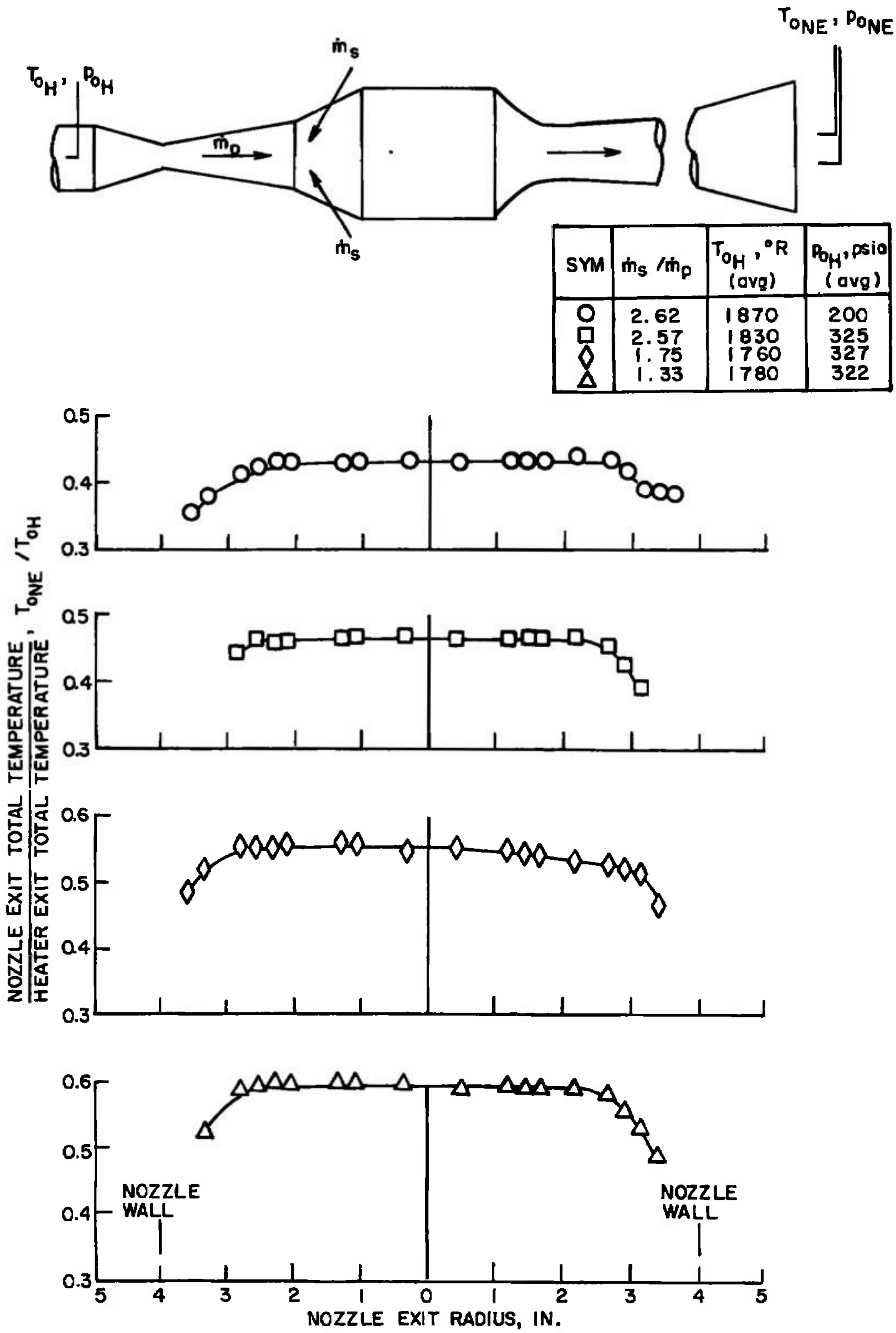


Fig. 14 Mach 4.0 Nozzle Exit Pressure Profiles, Configuration B



SYM	$\dot{m}_s/\dot{m}_p$	T_{0_H}, °R (avg)	p_{0_H}, psia (avg)
○	2.62	1870	200
□	2.57	1830	325
◊	1.75	1760	327
△	1.33	1780	322

Fig. 15 Mach 4.0 Nozzle Exit Temperature Profiles, Configuration B

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) Arnold Engineering Development Center ARO, Inc., Contract Operator Arnold Air Force Station, Tennessee	2a REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b GROUP N/A

3 REPORT TITLE

AN EXPERIMENTAL INVESTIGATION OF MIXING HIGH TEMPERATURE AIR WITH AMBIENT BYPASS AIR BY UPSTREAM INJECTION

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

N/A

5 AUTHOR(S) (Last name, first name, initial)

Henson, J. R., ARO, Inc., and Simmons, C. E., 1st Lt, USAF

6. REPORT DATE November 1966	7a TOTAL NO OF PAGES 38	7b NO OF REFS 6

8a CONTRACT OR GRANT NO AF40(600)-1200 b. PROJECT NO. 7778 c Program Element 62410034 d. Task 777805	9a ORIGINATOR'S REPORT NUMBER(S) AEDC-TR-66-146 9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report) N/A

10 AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES Available in DDC	12. SPONSORING MILITARY ACTIVITY Arnold Engineering Development Center, Air Force Systems Command, Arnold Air Force Station, Tennessee

13 ABSTRACT

A mixing chamber employing upstream injection of the secondary airflow was designed and tested in conjunction with a Mach 4.0 nozzle. Mixing chamber configurations with total length to maximum diameter ratios of 1.7 and 2.3 were investigated. The mixer was designed for a secondary to primary mass flow ratio of 2.57 and a primary to stilling chamber pressure ratio of 4.78. A uniform temperature profile with not more than 5 percent variation at the exit of the Mach 4.0 nozzle was required. The mixing chamber was experimentally investigated at secondary to primary mass flow ratios of 0.86 to 2.70. The primary mass flow ranged from 0.99 to 1.5 lb/sec at temperatures from 1730 to 2240°R, depending upon the heater flow rate. The secondary flow temperature was approximately 470°R. Temperature and pressure profiles obtained in the mixing chamber and 0.5 in. downstream of the Mach 4.0 nozzle exit substantiated satisfactory mixer performance.

DD FORM 1 JAN 64 1473

Security Classification

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. mixing chambers high temperature air injection temperature profiles supersonic flow 1-2 2. Air -- Mixing 3. High temperature air -- Mixing 4 Ambient air -- "						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
______________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
______________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
______________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Security Classification